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THE CONFIGURATION PROBLEM OF MICROWAVE CONNECTIONS IN UTRAN

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Abstract

The spectral efficiency of microwave networks can be greatly improved by properly selecting and configuring the microwave equipment. Configuration trade-offs and network optimization techniques influencing the spectral demand have been investigated in the presented simulation experiments.

Keywords: network configuration, microwave access networks, interference, frequency allocation, link planning.

1. Introduction

The 1–30 GHz part of electromagnetic waves (according to 300–10 mm wavelength) is called the microwave band. Microwave links (like Ericsson's MiniLink product family [4, 5]) have been frequently chosen to build terrestrial networks when ownership, fast roll-out and small operational costs are important. Microwave links especially suit the requirements of cellular network operators, who already have sites and towers for the cellular radio base stations. These mounting platforms can also accommodate the microwave links that connect the base stations to the backbone network.

The work is motivated by the challenges of the UMTS Terrestrial Access Networks (UTRAN), where the density of radio base stations is higher than that in GSM. The chance for interference in the backhaul microwave network will also increase and that will certainly have an impact on the capacity and cost of UTRAN.

In some countries, the lower part of the spectrum reserved for microwave telecommunications is already crowded due to the heavy usage by cellular operators. Network planners are forced to choose higher frequency bands (but higher frequencies are more sensitive to rain and fog) or forced to apply interference analysis before link deployment or link upgrade.

Frequency-channel allocations in microwave telecommunications are in accordance with one of two main policies: 1) channels for individual, or multiple links are approved by a central authority with the condition that existing installations are not interfered; 2) entire channel blocks over a geographical region are licensed to certain network operators, who then manage freely the channel allocations for their own links. In the latter arrangement, reconfiguration of already operational links is possible if interference hinders network expansion. When dealing with network configuration, both policies have to be applied. Usually the second one is dominant.

Recently, microwave links of a novel kind have appeared in the market. This is the point-to-multipoint type (PtMP), which has advantages over the traditional point-to-point type (PtP) when the task is to aggregate traffic into concentration points like in cellular networks. The terminals in multipoint type connections use time division multiple access (TDMA).

The presented network analysis is based on computer simulations, in which a blend of combinatorial optimization techniques is applied. Artificial network topologies, which resemble real deployments and involve both PtP and PtMP links, are generated in great numbers. Then the links of each network are configured in an interference minimization procedure. Finally, the statistics computed over similar network samples lead to predictions on the required spectral resources, or alternatively, on the reliability of the examined microwave networks.

2. Related Work

2.1. Link Planning

Planning and configuring individual microwave links is an established procedure. Radio transmission models are well known. In our current scope we do not deal with modulation and data representation aspects. The base model consists of a radio transmitter, a radio receiver, and a transmission channel between them. The transmitter is characterized by its transmit power and antenna gain, which are direction and polarization dependent. The receiver has a similar antenna gain, and the sensitivity is also given for bit/error-ratio.

There are more accurate and detailed transmission representations as well. When we model the transmit channel, then path loss and different fading types have to be considered. There are several methods to calculate path loss from the basic free space propagation assumption to complex calculations with diffractions. The latest computer-aided network design tools have sophisticated wave-propagation predictions over terrains given by high-resolution digital elevation maps [6]. Fading is due to multipath propagation, rain and moisture. The movement of the transmitter or the receiver causes fading too. Fading is frequency dependent. Well-known fading-calculation models are for example the Rayleigh-, or Rician-fading calculation.

Novel computer tools also analyze co- and adjacent-channel interference among radio links and some have support for automatic frequency allocation. Thanks to the built-in equipment library and GIS database, they are indispensable in configuring individual microwave links.

However, these tools are not designed to analyze deployment strategies in general, and they cannot perform complex optimization. Multivariate optimization is essential for the investigation of interactions and trade-offs among the various equipment and network parameters.

2.2. *Frequency Allocation*

The frequency allocation of radio networks has been a classic study area of optimization theorists and this topic got into the centre of attention, when large-scale deployments of cellular networks started. The mathematical approach to frequency allocation formulates the task as a graph colouring/labelling problem [13, 9, 10]. Compared to link planning, here whole networks are considered with huge simplifications. A so-called interference graph is built, where the vertexes are the radio cells/nodes or radio connections. The edges between the vertexes represent the fact that different colours (frequencies) have to be applied for the connected nodes, because using the same frequency leads to unacceptable interference.

2.2.1. Frequency Allocation Problems (FAPs)

There are a couple of famous frequency allocation problems. Without the detailed mathematical description (for further information see [3, 1, 16]), the most important for us are the next ones:

- Feasibility frequency allocation problem (F-FAP): The goal is to find the needed number of frequencies for each vertex in a way that the restrictions in the interference graph are not hurt (this is a feasible solution). Because in practical cases such a solution rarely exists, the problem should be relaxed. We cannot find a feasible solution, but still we can try to find a good solution, or choose the available best one.
- Maximum service frequency allocation problem (MAX-FAP): If a feasible solution is not available, we can find a partial solution that assigns less than the needed, but as many frequencies as possible to the vertices.
- Minimum order frequency allocation problem (MO-FAP): If feasible solutions exist, we may look for the most inexpensive one. This means minimizing the total number of the frequencies used in the network.
- Radio link frequency allocation problem (RL-FAP) [2]: The goal is similar to MO-FAP, but here a new parameter is introduced: the weight of the edges in the interference graph means the needed exact or minimal difference between the frequencies of the nodes.

- Minimum span frequency allocation problem (MS-FAP): In this problem one is supposed to pay for the full set of frequencies between the highest and the lowest ones used. The difference between them is called the span. This span is similar to the width of the licensed radio spectrum. In this problem the goal is to minimize it.
- Minimum interference frequency allocation problem (MI-FAP): The interference data from the interference graph is not simplified in this case to an allowed/not allowed state. The goal is to minimize the sum of the so-called penalties related to the interference.

This problem classes give a short overview of the possible goals to our work.

2.2.2. Heuristic Approaches

Due to the difficulty of the diverse FAPs, the majority of research has been made on heuristic methods. Common ways to solve similar problems are presented here:

- Greedy methods are used in most cases to generate starting solution to other algorithms.
- Local search methods start with a given solution and with iteratively doing small changes – called movements – they try to find good solutions. Only improving moves are allowed.
- Tabu search allows worsening moves under certain conditions related to neighborhood restrictions.
- Simulated annealing allows worsening with a probability that depends on the amount of the worsening, and is decreasing in time.
- Genetic algorithms start with a set of solutions and iteratively build new generations by recombination of solutions from the previous generation [15].
- Neural networks (artificial ones) generate solutions by emulating the behaviour of a grid of neurons. Each neuron represents a piece of the solution, and its state is dynamically determined by the states of its neighbours [17].
- Ant colony optimization is a meta-heuristic inspired by the behaviour of ants and based on greedy methods.
- Mathematical programming formulation based and constraint programming heuristic solutions are also available, but they are out of our scope.

Because these are heuristic methods, generally none of them can be termed as the best one.

These frequency allocation methods handle interference with simplifications, meanwhile they rarely include parameters such as transmit power, polarization and antenna size in the optimization. Accordingly, the results are mostly theoretical.

3. Model

The methods of this study are between the above two approaches (2.1 and 2.2). The main idea in this work is their proper combination. The focus herein is neither on the optimization theory, nor on the design of a particular network or link, but on network tuning techniques, which might efficiently mitigate interference in certain classes of networks.

In this section our model will be presented.

3.1. Configuration Process

The configuration of links is carried out in the frequency planning procedure, where the frequency band and channel, as well as the antenna size, polarization and transmit power are assigned to the links.

The network design and performance evaluation steps are the following:

1. Decide on the network scenario to be analyzed: Determine how the nodes are generated for the tests.
2. Generate randomly a number of node maps with the above parameter settings. These maps make up the population of network instances that the statistics is based on.
3. Design cost-optimal, hierarchical UMTS access network (see [8, 7]) on each map instance generated in the previous step.
4. Configure the radio links in each network instance such that the interference minimization objectives are met.
5. Evaluate the spectral demand or the data losses due to outages for each network instance, then derive performance-related statistics over the network population.

3.2. Access Networks

This study focuses on access networks which are part of cellular telecommunications. The elements of such networks are:

- The cellular radio base stations and the concentration nodes, where the traffic is aggregated. The concentrator nodes are the hubs and the radio network controllers. All these nodes are given with their co-ordinates and traffic.
- The transmission links that form a hierarchical network topology over the nodes. All links are assumed to be microwave with frequency-division duplexing. They are associated with a capacity and type during topology planning. The link type could be PtP or PtMP.

The microwave links are described by the following parameters:

- The frequency band of operation.
- By assuming frequency division duplexing, the upper and lower frequencies are assigned to the transmit directions, further referred to as setting the FDD direction.
- The size of antenna is selectable from a set of fixed sizes; the antenna patterns are given by the antenna gain, by the dimensions of a Gaussian main lobe and by the radiation masks outside the main lobe; the cross-polarization antenna pattern is approximated by a fixed suppression value for any combination of antenna size and frequency band.
- The maximum and minimum power that a transmitter is capable. The transmit power can be tuned between these values.
- The receiver sensitivity at the specified bit-error ratio.
- An arbitrary extra link loss beyond the free-space propagation loss can be given for any pair of nodes in the network. Yet, the assumed wave propagation is an unobstructed line of sight over a plain surface, since any other assumption would introduce terrain-related implications, which this study does not aim to track.

3.2.1. Network Instances

Randomly generated nodes [7] make the input to the experimental algorithms. One method generates node locations and node traffic according to uniform distributions, while another method places nodes around certain locations with a higher probability in order to simulate realistic settlements. The basic network parameters are 1) the density of nodes, 2) the number of nodes in the network, 3) the degree of clustering for the simulation settlements.

3.2.2. Link Planning

The design tool by [7] places the radio links and selects the concentration points while it optimizes the equipment cost. Beyond the actual cost of the various equipment items, the design algorithms have many selectable parameters, for instance, which control the placement of PtMP links.

3.3. Simplifications

As you can see from the model above, there are several free radio parameters in the model:

- For each link, the polarization, the FDD direction, the transmitter power, the transmission channel and the antenna type can be chosen.

- Globally, the number of the available channels and the width of each channel are free to set.

Simplifications are needed to be able to handle the problem. In our current work the next ones are applied:

- Line of sight visibility model is used, with a possible extra propagation loss between the node-pairs
- The model is in plain terrain, 3 dimensional aspects are not examined
- Adjacent channel interference and frequency intermodulation are out of scope
- Constant cross-polarization suppression is used instead of direction-dependent suppression
- The frequency channel width is fixed and the same, regardless of link capacity
- Constant equipment is used (26 GHz, 0.6 m antenna). It means that finding the best equipment for the network is not a goal for us.

These simplifications allow an acceptable running time and complexity.

4. Problem Description

Based on the model presented in the previous section the general problem definition can be given as:

- The input of the problem consist of:
  - The network nodes
  - The links between them,
  - The node-to-node visibility matrix
  - The antenna characteristics
  - The solution objectives: required fading margin or the number of available channels
- The output solution is:
  - The radio parameters for each link: power, polarization, FDD direction, channel
  - The projected data loss in the network as a measure of the solution
- The goals are:
  - Not to violate the input solution preferences
  - To minimize data loss

4.1. Hardness

The hardness of the problem can be discussed from a theoretical and from a practical point of view.

4.1.1. *Theoretical Hardness*

To get an overview of the theoretical hardness, a comparison to the known FAPs is a good idea. Without the correct mathematical proving it can be shown, that MI-FAP is a sub-problem of our presented problem, because a similar frequency assignment is done in both cases, but we have to deal with additional radio parameters as well.

Some theoretical results concerning FAPs show (we suppose P does not equal *NP*) (see [1]) that:

- The 'easy' problems, for example RL-FAP, are in *NP*. It means, if we have a solution, it can be shown in polynomial time that it is correct.
- All presented FAPs are *NP*-hard (so the 'easy' ones are *NP*-complete due to the previous statement). It means that finding the best solution is not possible in polynomial time.
- MI-FAP is not in *APX*. Deciding if an instance of MI-FAP allows a feasible assignment is *NP*-complete. Finding the best from the instances is more complex than a feasibility check, we know, it is *NP*-hard. But not being in *APX* means that no assumption in polynomial time can be given with a limited difference from the optimal solution.

4.1.2. *Practical Hardness*

FAPs are theoretically hard. In practice a hard problem might be small or structured in a way that it can be handled efficiently. In our case this assumption is not valid; we can foresee it from the third theoretical result above.

The very high number of computations originates from the base step of the optimization: cost calculation. To get the cost, the interference between each node pair has to be calculated, which interference determines the outage probability. This calculation cannot be done in less than $O(n^2)$ steps, where n is the number of the nodes. When calculating this cost after changing just one link in the network, the number of the required calculation steps can be reduced to $O(n)$. But this $O(n)$ running time can be quite long as well, considering for example that $O(n) = O(c * n)$ where the c constant can be significantly bigger than n in the case of average problems.

This base cost-calculation step is repeated every time when the effect of a small change in the network is done by a heuristic method.

5. Interference Minimization

The objective of interference minimization can be twofold:

1. Find the minimally needed spectrum for the given microwave network, i.e. find the minimum number of channels so that the network performance (which

is measured by the projected outage and data loss) is better than the specified one.

2. Alternatively, adjust the microwave links to the available frequency channels, such that the projected outage and data loss are less than the specified one or as small as possible.

The trade-offs in tuning a microwave network, namely the selection of frequency band, antenna size and transmit power, have direct consequences to equipment price, as well as, to installation and maintenance costs. Examining all aspects of link configuration is not the scope of this study. Here the treatment of radio characteristics and electromagnetic wave propagation has been greatly simplified (see 3.3), yet, the results from simulations will help to design deployment policies and lead to efficient configurations.

The interference minimization algorithms use the projected data loss in the network for the meteorologically worst month as the cost function [14]. This measure is based on ITU [11, 12] recommendations, which suggest the worst month of the year, the geoclimatic factor and the typical rain rate for all geographical regions of the world. The ITU standards also provide various algorithms to estimate the propagation loss for microwave links. The factors above, together with the accomplished fading margin permit the prediction of outage probability on a particular microwave link. By weighing the outage probabilities with the corresponding data rate and summing them for all microwave links in the network, one can establish a performance measure for microwave networks:

$$\text{Data\_loss} = \sum_{\text{for\_all\_links}} \text{Traffic} \cdot \text{Outage}$$

5.1. *Optimization Steps*

The topology planning tool is not aware of interference when it connects the nodes (see 3.2.2). The transmit power, polarization, FDD direction and frequency channel for the links are adjusted by a separate interference minimization module. Four steps, each dedicated to one parameter, perform these tasks. The methods are based on a local search approach (see 2.2.2). Combinations, repetitions of these optimization steps are possible. The basic steps are described below.

5.1.1. *Power Adjustment*

The power adjustment algorithm tries to find the best transmit power for each transmitter. This best means the best from the point of view of the whole network, not from the point of view of a single link. Insufficient fading margin on a link jeopardizes the operation if rain or multipath propagation phenomenon occurs. A fading event can cause high bit-error ratio or temporary shut down on the link. On the other hand, overly high transmit power might cause interference to other links, so an iterative search is carried out to reach the best balance.

Initially, transmit power is set to compensate the path loss and to reach the fading margin that is sufficient for the specified performance if no interference occurs. Then the interference is computed for all nodes and starting with the most impaired link, the power is raised. The amount of this raising can be a fixed value or a computed level where the fading margin satisfies the requirement even with the previously computed interference. (For a comparison see 6.3). If the new power level brings improvement, then it is kept. This action is repeated on the remaining troubled links in an iterative process until fading margin at all links is sufficient, or not improving anymore with further iterations. The iteration also terminates after a maximum number of rounds.

5.1.2. Polarization Setting

Orthogonal polarizations are exploited in this optimization step. Typically, horizontal or vertical polarization can be chosen for PtP links, but in PtMP systems, all terminals connecting to a hub must have the polarization of the hub. The received signal with orthogonal polarization is suppressed by the cross-polarization suppression.

Initially, all hubs and links have the same polarization. Like the power setting, polarization is iteratively flipped for the most troubled link or PtMP hub. The modification is kept if it leads to less overall interference, if not, then the step is revoked. This is repeated on the remaining troubled links until fading margin at all links is sufficient, or not improving anymore with further iterations.

5.1.3. Setting the FDD Direction

This algorithm is like the polarization setting method for PtP links. For PtMP links, the FDD direction is fixed.

The method starts from the situation where the FDD direction is the same for each link as the direction of the link (pointing to concentration nodes or core network). Then this direction is iteratively changed as shown before.

Both the fading margin and cross-polarization suppression improve with selecting larger antennas; however, this has its consequences in equipment and installation costs.

5.1.4. Frequency Channel Adjustment

Interference can be eliminated with the addition of new channels. This ultimate option is used if the previous algorithms do not accomplish the goals. Two kinds of frequency assignment policy have been implemented:

(i) The required fading margin is assured even if extra channels have to be allocated in exchange. In this case, the number of channels is not limited.
(ii) The number of channels is limited, hence the fading margin is maximized on troubled links to get as close to the desired level as possible.

Initially all links are set to a single channel, and the other optimization steps are tried first. Then the link impaired the most by interference is tuned to an alternative frequency band or channel and the iteration steps through the troubled links. This operation is repeated for the links on the alternative channel until the fading margin is sufficient on all links, or the allocable channels are exhausted.

The adjacent channel interference and frequency intermodulation are not examined; hence no condition on neighbouring channel allocations is taken into account.

The optimization provides a fully configured microwave network. The network topology itself is cost-optimal, while the frequency band, channel, power, polarization and FDD direction are set to a reached minimum interference. In addition, the projected data loss in the worst month as a cumulative measure expresses the performance of optimization or the traits of the network type under test. The network instances of a kind are characterized by statistics.

Already configured parts of the network can be set as unchangeable by optimization, so network expansions and upgrades can be studied as well.

6. Results from Simulation Experiments

Fig. 1 shows the projected outage of a PtP microwave network after performing the presented basic interference minimization steps one-by-one. The network is of the settlement type containing 200 nodes with traffic between 2 and 4 Mbps.

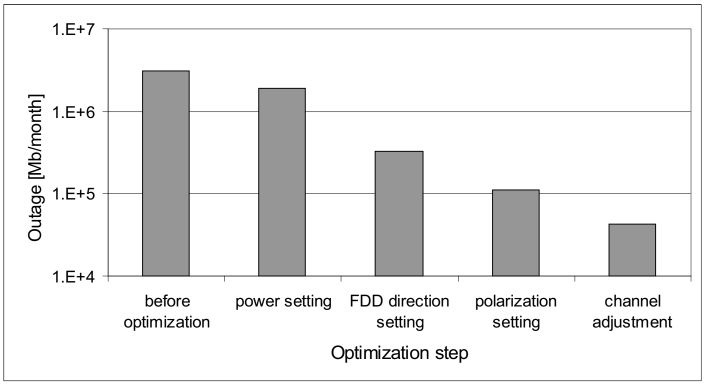

Fig. 1. An example for the optimization process

Compared to the single-channel, single-polarization and time-domain duplexing case with initial power settings, the four optimization steps decrease the overall interference typically by two magnitudes with two frequency channels.

Based on the statistics, the order of steps does not seem to matter.

6.1. *The Comparison of Optimization Steps in PtP Networks*

By performing only one of the basic steps, the optimization efficiency of those can be evaluated. *Fig. 2* shows the results. With the present settings of frequency band (26 GHz) and antenna diameter (0.6 m) both the FDD direction and polarization adjustment are equivalent to adding an extra channel. The statistics is based on 20 PtP network instances with a mean path lengths between 1.1 and 1.4 Km.

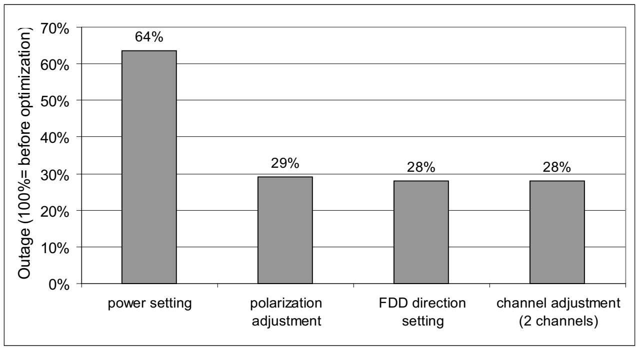

Fig. 2. Comparison of the 4 basic optimization steps

As you can see power setting is less effective than the other steps. This is according to what we expected. The little difference between polarization adjustment and FDD direction setting is due to the fact that the cross-polarization suppression is high but not infinite. If it would be infinite (meaning an ideal polarization separation of the antennas), the efficiency of these steps would be equal. FDD direction setting and channel selection in the case of two channels seem to have the same effect. Channel setting gives more freedom compared to FDD direction setting.

6.2. *The Efficiency of Optimization Steps in PtP Networks*

The presented methods are based on the local search approach. Usually a greedy method is used to get an initial solution, which then will be improved by local search. In our case, practically every configuration is a suitable solution, but of course most of them are quite expensive (with a huge traffic loss). By starting different starting solutions one can get a view about the efficiency of local search.

Instead of the same polarization (see 5.1.2), randomly chosen polarizations were applied to each link. The results are compared in *Fig. 3*.

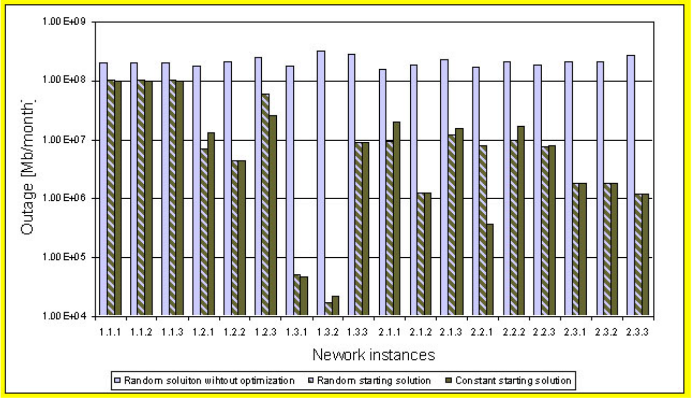

Fig. 3. The effect of choosing a starting solution

Statistically it does not make any difference how the starting solution is chosen. Our methods can benefit from this fact, which allows us to make several runs with randomly chosen configurations in order to avoid getting stuck in local minimum far from the global optimum.

6.3. *Optimizing the Transmit Power*

This optimization step increases the transmit power on interference-troubled links. One round is when all interfered links are adjusted once. Interference is re-evaluated after each round.

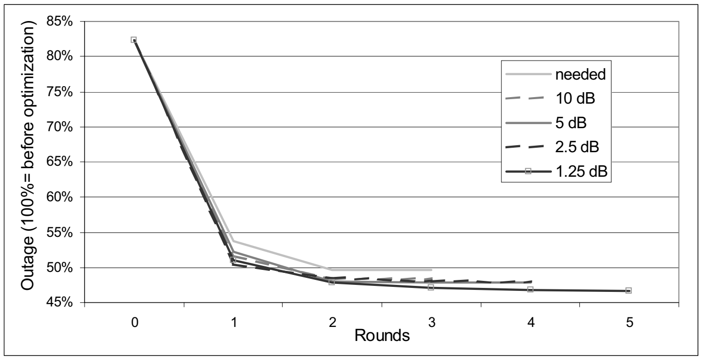

Fig. 4. Convergence of power optimization

Fig. 4 shows an example how the projected network outage decreases round-by-round. Interestingly, adjusting the power right to the desired fading margin in one step is not as effective as making the adjustments in cautious steps. This behaviour can be explained by the fact that more iteration with fixed steps gives more freedom than simply the option of setting to a single value.

6.4. Impact of Topology Design

The network-planning algorithm produces topologies, which do not differ much in interference (c.a. 5–10%) before optimization. However, specific instances in the population are problematic from the viewpoint of interference elimination.

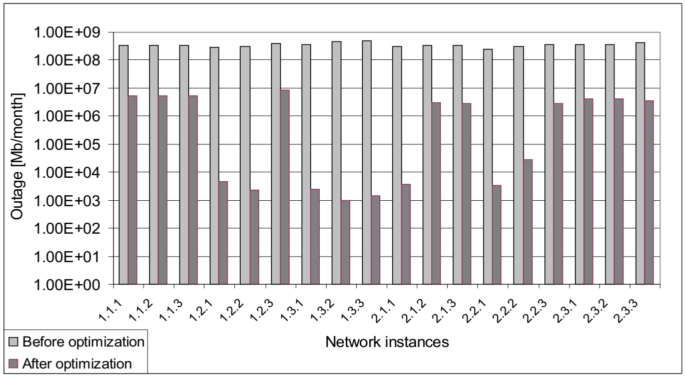

Fig. 5. Network instances before and after optimization

As you can see in *Fig. 5*, seemingly minor differences in topology cause large differences in residual interference. The outage measure after optimization has a relative standard deviation of 40–50% in the population.

It has been observed that the cost and interference optimum barely coincide in a population of similar topologies. Low equipment costs are typically paired with high interference, and high costs with low interference.

6.5. Deployment in Phases

In this experiment, the spectral efficiency of networks that are deployed 1) link by link, 2) in two phases, 3) in one batch is compared.

When links are placed one by one, the rule is that already deployed links cannot be modified. Analogously, deployment in phases means that links deployed in previous phases cannot be re-configured. The optimization adjusts only the links planned for the current phase with the condition that already established links should not be interfered. At last, deploying in one batch practically means that all links in the network are subject to optimization.

Table 1. Comparison of deployment strategies

Link by Link	In Two Phases	In One Batch
262	118	42

Table 1 lists the projected outage in [Gb/month] for a population of 20 PtP network instances as deployed by the above three methods. The instances contain 200 nodes and were subjected to all optimization steps with 2 channels.

6.6. PtP vs. PtMP

When the density of nodes reaches a certain level, PtMP links become financially more economical than PtP links. However, the disadvantage is, that PtMP systems require a wider frequency band. The options of the link planner algorithm control whether only PtP, PtMP or a cost-optimal mix of those links are planned.

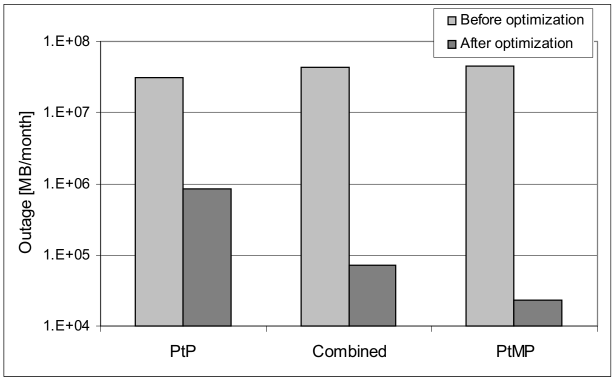

Fig. 6. Comparison of PtP and PtMP networks

These variations are compared in *Fig. 6.* Two channels, separate ones for the PtP and PtMP links, are used in each case. The measurements are based on 10 map instances. In the mix, about 85% of the links are PtMP.

7. Conclusion

In the studied PtP networks, optimization reduced interference to 1–5% of the initial value by adding the orthogonal polarization, a second channel and by systematically setting transmit power and FDD direction.

Cost-optimal planning of network topology might result in acute trouble spots from the viewpoint of interference. The best planning practice is to take interference-related conditions into account already in the topology design of microwave networks.

Greedy algorithms have difficulty with the large number and variety of optimization variables involved in link configuration. After divide and conquer, the basic optimization steps seem to be independent and interchangeable.

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